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# A Preliminary Analysis of Ground-Water and Surface-Water Radioactivity Around the Main Injector Extraction and Injection Regions

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**Abstract**

The Main Injector is a new high intensity 150 GeV proton accelerator that will replace the existing Main Ring for collider operation of the Tevatron, and for fixed target experiments. In this report, we estimate the radioactive contamination of $^{3}H$ and $^{22}Na$ nuclei, which are produced due to particle beam interaction with beam line elements in the extraction and injection regions of the Main Injector. Our study suggests that additional protection is needed at some locations to be in compliance with DOE/EPA standards for ground and surface water activation levels.

## 1 Introduction

The Main Injector at Fermi National Accelerator Laboratory will be the newest addition to the accelerator complex. The goal of the Fermilab Main Injector Project is to construct a new high intensity 150 GeV proton synchrotron on the Fermilab site in support of the Fermilab High Energy Physics (HEP) research program. With the construction of this accelerator, the lab will be capable of supporting both the collider and 120 GeV fixed target programs simultaneously.

The Fermilab Main Injector is located south of the Antiproton Source and tangential to the Tevatron ring at the F0 straight section, as shown in Figure 1. The Main Injector enclosure and its beam lines are situated about 7.62 m (25 ft) below the surface level with a minimum soil equivalent shielding of about 7.46 m (24.5 ft) around the ring. The Main Ring will cease to exist following commissioning of the Fermilab Main Injector. This project started around August of 1991, and is now nearing its commissioning phase; preparations are now being made as it goes into its final phase of construction [1].

During the course of normal operation, the Main Injector, like any particle accelerator, can produce radionuclides in the adjacent soil and in the beam line elements. The Fermilab Main Injector Preliminary Safety Analysis Report states that, in order to reduce radionuclide concentrations to acceptable levels, additional shielding will need to be provided in the vicinity of certain components, such as the extraction septum, which are inherently lossy [2]. Parameters such as soil content, beam intensity, and the energy of the beam, determine the production and concentration of the radionuclides. The only soil leachable radionuclides of concern that are produced in the Fermilab soil are $^{3}$H, $^{7}$Be, $^{22}$Na, $^{45}$Ca and $^{54}$Mn [3]. Among them, tritium ($^{3}$H) is of particular concern because it readily bonds to oxygen molecules, forming a highly mobile radioactive water molecule, capable of contaminating underground drinking reservoirs and surface waters [2-5]. In like manner, when $^{22}Na$ bonds and becomes a salt, it readily dissolves in water and becomes highly mobile. Tritium ($^3H$) is an isotope of hydrogen with a half-life of 12.3 years, and $^{22}Na$ is an isotope of sodium and has a half-life of 2.6 years. Because of their longer half-lives and greater leachabilities, $^3H$ and $^{22}Na$ were the primary focus of this investigation. Some relevant properties of these two nuclei are listed in Table I.

Table I
Production probabilities, mean life, leachability factor for radioactive nuclei produced in the soil, and the DOE/EPA allowed concentrations

| Nuclei | Production Probability $K_i$ (per star) | Leachability Factor $L_i$ | Mean life $\tau_i$ (yr) | Allowed Concentrations $G_i$ $(pCi/ml - yr)$ |
|---|---|---|---|---|
| $^3H$ | 0.075 | 0.9 | 17.7 | 20.0 (Ground Water) |
| $^{22}$Na | 0.02 | 0.135 | 3.75 | 0.2 (Ground Water) |
| $^3H$ | 0.075 | 0.9 | 17.7 | 2000 (Surface Water) |

Along the entire beam line, there exist few places that have high enough radiation fields to produce significant quantities of radionuclides in the soil outside of immediately controlled surroundings. These areas include the injection and extraction sectors, beam stops, and target stations. In the case of injection and extraction regions, one expects beam losses due to lattice mismatches and due to extraction septum wires in the case of slow extraction. The former type of beam loss can always be minimized, or even eliminated, by diagnosing the causes and tuning the beam line elements. However, the second type of beam loss cannot be eliminated because of the finite dimensions of the septum wires. Hence, special precaution must be taken around the injection and extraction septa. This report summarizes a predictive modeling performed to assess the migration and fate of injection/extraction region-produced radionuclides within the ground water and the surface water around the Main Injector. Several injection and extraction regions, seen in Table II, were selected for evaluation (see also Figure 2).

Table II
The Location, Function, and Dimensions of Evaluated Straight Sections

| Location | Function | Floor Slab Thickness m (ft.) | Ceiling Thickness (ft.) |
|---|---|---|---|
| MI 10 | 8 GeV Injection | 0.61 (2.0) | 0.46 (1.5) |
| MI 30 | Slow extraction of 120 GeV Beam | 0.76 (2.5) | 0.46 (1.5) |
| MI 40 | Fast Extraction Towards Beam Absorber | 0.53 (1.75) | 0.46 (1.5) |
| MI 52 | Slow Extraction | 0.61 (2.0) | 0.46 (1.5) |
| MI 60 | Fast Extraction of Protons to NuMi | 0.53 (1.75) | 0.46 (1.5) |
| MI 62 | $\bar{p}$ extraction | 0.53 (1.75) | 0.46 (1.5) |

A preliminary safety analysis has been made for the Main Injector complex [2]. This suggests that the total normal operational loss should be less than $5.4 \times 10^{18}$ per year at 120 GeV. The present assessment should be in compliance with this limit.

## 2 Hydro-geology Around the Main Injector Site

The migration of the radionuclides in the soil ground water sources is largely dependent on the soil properties and the hydro-geology of the site [6]. A large source of water that is available for domestic use is found in aquifers, which are underground water-bearing rock formations. Around the Fermilab site, the ground water flows horizontally through the aquifer's upper layer of bedrock. Above the aquifer, ranging from 40 to 70 feet in depth, sits the glacial till. The water moves from surface to aquifer at a rate dependent upon the permeability of the soil.

There are ten drinking water wells present on the Fermilab site, all of which are located in Silurian Dolomite bedrock. The Silurian Dolomite is generally 30 m (100 ft) to 60 m (200 ft) thick. Figure 3 shows the location of these wells on the Fermilab site. The well at the F17 location is the nearest drinking well to the MI site. There are several man-made ponds and creeks on site; however, these are not connected to the ground water sources. The primary purpose of the ponds is to provide cooling water for the Main Injector magnets, and for fire protection [1].

A geologic cross section of the MI40 site is shown in Figure 4 [6]. In the absence of similar geologic cross sectional views of other locations of interest we assume the MI40 case is representative for the Main Injector Ring. The top elevation of the Silurian Dolomite in this region is at about 206.3 m (677 ft). The potentiometric map, derived from the information at well F17, indicates the water level in the dolomite is at 209.4 m (687 ft). The Environmental Assessment of the Fermilab Main

Injector Project indicates yet another elevation of the ground water level around Main Injector site [7]. Since the elevations of the drinking water wells in and around the Fermilab are at, or lower, than dolomite level, it has been recommended to use 206.34 m as the ground water level [8] .

The object of this study is to present a realistic simulation of radionuclides transport from the MI to ground water aquifers and surface water sump pumps. These model results will be utilized to estimate the required shielding at the loss points so as to keep the radioactive contamination below DOE/EPA acceptable limits shown in Table I.

## 3 CASIM

To calculate the amount of $^{3}H$ and $^{22}Na$ produced in the soil around Main Injector sites, a Monte Carlo simulation computer code, CASIM is used [9]. CASIM simulates the development of the hadronic cascade at the beam loss point and its surroundings. The program uses inclusive distributions of particle yields as a function of the angle and momentum from inelastic particle-nucleus interactions, and simulates the average development of inter-nuclear cascades when high energy particles are incident on a large target of arbitrary geometry and composition. The quantities called 'star densities,' nuclear interaction densities as a function of three-dimensional coordinates and particle type throughout the target, are computed by the program. Using the probabilities for the $^{3}H$ and $^{22}Na$ nuclei per star, the total amount of individual radionuclide species in the soil can be estimated. From these star densities, estimates of a number of quantities of radio-biological interest, dose equivalent due to direct irradiation or due to exposure to remnant radioactivity, are obtained. (Figure 7 is a sample output showing the contours of equal star density (stars/ml/incident particle) for MI and the surrounding soil for 120 GeV protons).

## 4 The Concentration Model

To estimate ground water radioactive contamination, we use the Fermilab Concentration Model [4,5]. This model is based upon individual site hydro-geology. According to this model the initial concentration of the $i^{th}$ radioactive nuclide, $C_i^{initial}$, in units of $(pCi/ml-y)$ is given by,

$$C_i^{initial} = \frac{N_p \cdot 0.019 \cdot S_{Max} \cdot K_i \cdot L_i}{1.17 \times 10^6 \cdot \rho \cdot \omega_i} \tag{1}$$

where

$N_p$ is the annual proton intensity lost at a point of interest.

$S_{Max}$ is the maximum of the star density/incident proton produced in the unprotected soil (i.e., the soil surrounding the beam line tunnel enclosure).

$\rho$ is the soil density (2.25 gm/ml for moist soil),

$\omega_i$ is the weight of the water divided by the weight of the soil that corresponds to 90% leaching (0.27 for $^3$H and 0.52 for $^{22}$Na).

The final concentration in the ground water, $C_i^{final}$, is related to the initial concentration by,

$$C_i^{final} = C_i^{initial} \cdot R_{till} \cdot R_{mix} \cdot R_{dolomite} \tag{2}$$

where $R_{till}$ is a reduction factor due to vertical migration and radioactive decay occurring during transport to the glacial till from the lowest boundary of the '99% volume' to the top of the dolomite aquifer. It can be calculated according to [4],

$$R_{till}(^3H) = 1.0 \cdot e^{(-0.3 \cdot d)} \tag{3a}$$

$$R_{till}(^{22}Na) = 1.0 \cdot e^{(-0.92 \cdot d)} \tag{3b}$$

where d is the distance from 1.84 meters below the point of maximum star density to the aquifer.

$R_{mix}$ is a reduction due to the mixing of the water containing the accelerator produced radioactivity with water at the glacial till/dolomite interface.

$R_{dolomite}$ is a reduction due to the mixing and radioactive decay occurring in the transport to the Fermilab site boundary or nearest well. The most conservative assumption is to assume instantaneous mixing, which results in assuming both $R_{mix}$ and $R_{dolomite}$ to be unity [5].

Furthermore, according to reference [3-5], the sum of the ratios of concentrations to their allowed regulatory limits must be less than one to insure that the annual 4 mrem/yr limit for community drinking water supplies is not exceeded:

$$\sum_{i=1}^{n} \frac{C_i}{G_i} \leq 1.0. \tag{4}$$

where $G_i$ is the allowed concentration of the $i^{th}$ radio-isotope, given in Table I.

In the case of surface water, the radionuclide concentration is obtained by the method illustrated in the recent study of AP0 beam stop [8]. Here, one assumes that the water collected in the sump, situated at the tunnel floor level along the accelerator, will be pumped out and disposed off to the surface. The yearly contamination in the surface water is given by:

$$C_{an}^{surface} = \frac{N_p \cdot S_{Avg} \cdot K_i \cdot L_i \cdot (1 - e^{-1/\tau_i})}{1.17 \times 10^6 \cdot \rho \cdot \omega_i} \tag{5}$$

The quantity $S_{Avg}$ is the average star density in the surrounding soil. It can be assumed that the radioactive contamination is flushed out due to water flow arising from rain fall. If one assumes accumulation of the radioactive nuclei, cumulative activity is given by:

$$C_{ac}^{surface} = \frac{N_p \cdot S_{Avg} \cdot K_i \cdot L_i \cdot (1 - e^{-1/\tau_i})}{1.17 \times 10^6 \cdot \rho \cdot \omega_i} \cdot \sum N_p^{year} \cdot e^{(years)/\tau_i} \quad (6).$$

where $N_p^{years}$ is the number of protons lost per year in the region of interest.

## 5 Results

The star densities estimated from Monte Carlo calculations performed for different tunnel configurations (shown in Table II) are listed in Table III. In our CASIM calculation, the beam loss point is assumed to be a target of about 15 cm radius and 4 m long. The distance between the tunnel floor and the MI beam line is 0.716 m (2.35 ft). Although the actual geometry of the MI tunnel shown in Figure 5 is rectangular, for calculational speed, a cylindrical geometry was used. Figure 6 shows a schematic of the modeled tunnel. To make conservative estimates, we took the tunnel radius to be 0.716 meters, that is, the shorter of the two distances, from beam-to-floor and beam-to-ceiling. A typical output from CASIM indicating contours of equal star densities is shown in Figure 7. Since the tunnel floor concrete thickness varies from 0.46 m to 0.76 m, we have variation of $\text{Star}_{Max}$ from location to location as shown in Table III. All these calculations assume point source.

The average star densities needed for evaluation of surface water contamination are estimated by counting the total number of stars produced in the uncontrolled soil outside the concrete wall which extends 1.0 m radially outwards and 20.0 m along the beam direction.

Final calculations are performed using an EXCEL spread sheet which uses Equations 1-6. The output of these calculations is illustrated in Appendix-A. One of the important parameters in the estimation of ground water is the distance between tunnel and ground water source 'd' at different locations. In Appendix-A, we compare the calculated contaminations for three different d's for each location explained previously.

Table III
Maximum and Average Star Densities in the uncontrolled soil

| Location | $Star_{max}$ (Stars/cc) | $Star_{avg}$ (Stars/cc) |
|---|---|---|
| MI 10 (8 GeV) | $1.00 \times 10^{-7}$ | $5.1 \times 10^{-10}$ |
| MI 30 | $1.00 \times 10^{-6}$ | $3.0 \times 10^{-9}$ |
| MI 40 | $1.30 \times 10^{-6}$ | $5.27 \times 10^{-9}$ |
| MI 52 | $7.50 \times 10^{-7}$ | $5.27 \times 10^{-7}$ |
| MI 60 | $1.00 \times 10^{-7}$ | $5.10 \times 10^{-10}$ |
| MI 62 | $1.00 \times 10^{-7}$ | $5.10 \times 10^{-10}$ |

Table IV lists the estimated yearly allowed beam losses assuming no additional shielding in the vicinity of the loss points. By comparing the results with the beam intensity limit set by Reference 2, we find that special attention should be given for the beam losses at MI30 and MI52 locations. Beam extraction at MI30 and MI52 involve electrostatic septum wires. The wire size and the gap between the wire and the cathode establish a lower limit on the beam loss; therefore, we can not eliminate beam losses completely. Methods have been suggested to reduce the beam loss at electrostatic septum by increasing the beta functions (lattice function) [10]. With the basic Main Injector lattice [1] we expect about 2% beam loss. During extraction the beam gets an initial 200 $\mu$r kick at MI30. A further kick of 400 $\mu$r is given to the beam at MI52 using two more electrostatic septa. If the phase advance is properly adjusted at MI52, all beam losses at this location should be eliminated. Hence, during the slow extraction, the potential beam loss point will be at MI30, and we have little control on MI30 beam loss. CASIM simulation suggests that the 2% loss at MI30 corresponds to a yearly beam loss of $6.82 \times 10^{18}$ protons, and ground water and surface water contamination will be as high as 1000 pCi/ml-yr and 900 pCi/ml-year, respectively. In order to be in compliance with the set concentration standards, with no shielding, the allowed beam loss must be less than $1.36 \times 10^{17}$ protons per year.

Table IV
Allowed Yearly Beam Loss for Radionuclide Limits

| Location | Allowed Yearly Beam Loss | Ground Water (pCi/ml-yr) | Surface Water (pCi/ml-yr) |
|---|---|---|---|
| MI 10 | $1.42 \times 10^{18}$ | 19.8 | 1.4 |
| MI 30 | $1.36 \times 10^{17}$* | 19.9 | 16.7 |
| MI 40 | $1.10 \times 10^{17}$ | 19.7 | 1.1 |
| MI 52 | $1.85 \times 10^{17}$ | 19.4 | 1.8 |
| MI 60 | $1.10 \times 10^{17}$ | 19.6 | 1.1 |
| MI 62 | $1.10 \times 10^{17}$ | 19.6 | 1.1 |

* This beam loss is about fifty times smaller than the estimated beam loss of $6.82 \times 10^{18}$ (2% of the annual total beam extracted).

Since MI30 is the only place of potential hazard from ground water as well as surface water point of view, further shielding analysis is carried out by adding shielding material around the extraction septum. The calculated star densities and the allowed beam intensities for different steel shielding configurations are listed in Table V.

Table V
Star densities and allowed beam intensity as a function of steel shielding thickness around MI30 for 120 GeV beam losses

| Shielding (meter) | Star Density (star/cc/p@120 GeV) | Allowed Beam Intensity (Annual) |
|---|---|---|
| No Shielding | 1.0E-6 | $1.36 \times 10^{17}$ |
| 0.33* | — | — |
| 0.54 | 7.74E-8 | $1.76 \times 10^{18}$ |
| .91 | 0.99E-8 | $1.35 \times 10^{19}$ |
| 1.22 | 0.71E-8 | $1.90 \times 10^{19}$ |

* No test run for 0.33 m shielding

## 6 Summary

A preliminary analysis of ground water and surface water radioactive contamination arising from operation of the Main Injector at Fermilab has been completed. Our study concentrates on the extraction and injection regions, or the potential beam loss points, around the Main

Injector. The concentrations of radionuclides in ground water have been calculated using the Fermilab Concentration Model. For surface water, we use a model discussed in Reference[8]. The allowed beam loss has been estimated for each location based upon the allowed limits of radionuclide concentration for $^{3}H$ and $^{22}Na$. As a result, major shielding is suggested around the MI30 slow extraction point.

The present preliminary analysis led to the conclusion that an additional shielding of 0.54 m (1.77 ft) of steel under the electrostatic septum reduces the ground water contamination only by a factor of 12. However, a total reduction by a factor of 50 is needed to meet DOE/EPA standards.

There are number of uncertainties in the the model used in the present analysis. One major uncertainty arises from the radiation source point. We have used point source of iron target of 15 cm radius and 4 m in length. In reality, the beam loss points, in the extraction region of the slow extraction system, will be an extended source of about 3.04 m long and thickness 0.0001 m (uniformly distributed along the septum). Hence, it may be necessary to take into account these details in the final calculation. Considerable improvement is anticipated in $Star_{Max}$ if such an extended source is used. Further work is being carried out in this regard.

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